

TITLE

COMPOSITION AND METHOD FOR MAKING FUEL CELL
COLLECTOR PLATES WITH IMPROVED PROPERTIES

FIELD OF THE INVENTION

5 This invention relates to conductive flow field separator plates having reduced resistivity and methods for making such plates. The plates comprise a liquid crystal polymer, poly(styrene-co-maleic anhydride) polymer and conductive filler.

BACKGROUND OF THE INVENTION:

10 The cost of fuel cells must be reduced dramatically to become commercially viable on a larger scale. The cost of the flow field plates, including the cost of forming the flow field onto the plate, represents a significant portion of the total cost within a fuel cell. Therefore, cost reduction of the flow field plate is imperative to enable fuel cells to become
15 commercially viable on a larger scale. The cost reduction can be manifested in several ways including reducing the cost of the materials that are used to make the plate, reducing the manufacturing cost associated with making the plate, and/or improving the function/performance of the plate within a fuel cell so that the same fuel
20 cell can produce electrical power more efficiently and/or produce more electrical power within the same fuel cell.

A typical Polymer-Electrolyte-Membrane (PEM) fuel cell comprises several components. These components typically include a membrane, catalyst layers on the anode and cathode sides of the membrane known
25 as the gas diffusion electrodes, and gas diffusion backings on each side. The membrane, electrode layers and gas diffusion backings are laminated together to create the membrane electrode assembly (MEA). Each MEA is sealed between two thermally and electrically conducting flow field plates. Each cell is then "stacked" with other cells to achieve the required voltage
30 and power output to form a fuel cell stack. Each stack is subjected to a compressive load to ensure good electrical contact between individual cells.

In operation, fuel is introduced on the anode side of the cell through flow field channels in the conductive flow field plates. The channels
35 uniformly distribute fuel across the active area of the cell. The fuel then passes through the gas diffusion backing of the anode and travels to the anode catalyst layer. Air or oxygen is introduced on the cathode side of the cell, which travels through the gas diffusion backing of the cathode to

the cathode catalyst layer. Both catalyst layers are porous structures that contain precious metal catalysts, carbon particles, ion-conducting NAFION® particles, and, in some cases, specially engineered hydrophobic and hydrophilic regions. At the anode side, the fuel is

5 electrochemically oxidized to produce protons and electrons. The protons must travel from anode side, across the ion-conducting electrolyte membrane, finally to the cathode side in order to react with the oxygen at the cathode catalyst sites. The electrons produced at the anode side must be conducted through the electrically conducting porous gas diffusion

10 backing to the conducting flow field plates. As soon as the flow field plate at the anode is connected with the flow field plate at the cathode via an external circuit, the electrons will flow from the anode through the circuit to the cathode. The oxygen at the cathode side will combine protons and electrons to form water as the by-product of the electrochemical reaction.

15 The by-products must be continually removed via the flow field plate at the cathode side in order to sustain efficient operation of the cell. Water is the only by-product if hydrogen is used as the fuel while water and carbon dioxide are the by-products if methanol is used as the fuel.

Conductive flow field plates comprise the outer layers of a fuel cell

20 and serve a number of functions: they provide structural integrity to the fuel cell; protect the fuel cell from corrosive degradation over the operating life of the fuel cell; and, most importantly conduct electrons and heat from the interior of the fuel cell to the exterior. Conductivity at the interface between the flow field plate and the outermost interior layer, i.e., gas diffusion layer, is critical for minimizing resistance in the fuel cell.

Because of the unique set of performance requirements of conductive flow field plates and the aggressive conditions inside the fuel cell, the material options for constructing conductive flow field plates are limited. In general, graphite has been used for conductive flow field plates

30 because of its high electrical conductivity and resistance to corrosion. Graphite however is typically produced in 6 mm thick slabs, adding both weight and bulk to the fuel cell and decreasing its power density when in use.

Carbon/graphite fillers in plastic polymers have been identified as a

35 promising alternative to graphite in manufacturing conductive flow field plates. Processes for preparing such plates are disclosed in U.S. Patent No. 4,124,747 to Murer and Amadei, U.S. Patent No. 4,169,816 to Tsien and U.S. Patent No. 4,686,072 to Fukuda.

While these carbon/graphite filler plates provide increased durability and flexibility to the fuel cell, the composition of carbon/graphite filler plates provides less than superior conductivity and resistivity (both bulk resistivity and through plane resistivity) properties. Attempts have been
5 made to reduce the resistivity of a molded plate by machining the surface of the molded plate to eliminate the polymer rich skin layer from the surface of the plate. Such machining processes however are time consuming and expensive.

Conductive fuel cell collector plates have been made with different
10 kinds of blends, including the following blends:

- a. Graphite filled liquid crystal polymer plates;
- b. Graphite filled polyvinylidene fluoride (PVDF) plates; and
- c. Graphite filled thermoset (vinyl ester) plates.

The use of graphite filled binary polymer blends for improving conductive
15 properties alongside other mechanical and thermal properties is well known. Some of the work done in this area includes:

- a. Wu et al 2001 (Wu G, Miura T, Asai S, Sumita M, "Carbon Black-Loading Induced Phase Fluctuations In PVDF/PMMA Miscible Blends: Dynamic Percolation Measurements", Polymer 42 (2001) 3271-3279) investigated carbon filled polyvinylidene fluoride / poly(methyl methacrylate) (PVDF/PMMA) blends. They found that the carbon black induces phase fluctuations in PVDF/PMMA blends to reduce percolation threshold.
 - b. Del Rio et al 1994 (Del Rio C, Acosta JL, Polymer 35 (1994) 3752) found that carbon black and Cu compatibilize polyvinylidene fluoride / polystyrene (PVDF/PS) systems and also result in improvement of electrical properties.
 - c. Del Rio et al 2000 (Del Rio C, Ojeda MC, Acosta JL, "Carbon Black Effect On The Microstructure Of Incompatible Polymer Blends", European Polymer Journal 36 (2000) 1687-1695) did a detailed study on the morphology and thermal properties of carbon filled polyvinylidene fluoride / polyamide 6 (PVDF/PA6) blends. They found that carbon black induces partial compatibilization and modifies isothermal crystallization kinetics in these blends.
- 35 The disclosures of all patents/applications and documents referenced herein are incorporated herein by reference.

There remains a need for a new composition for the conductive fuel cell collector plates with reduced resistivity and lighter weight without

compromising necessary plate conductivity and strength. Also, it is preferred to make the plates with cheaper materials to bring down the cost of the fuel cell.

SUMMARY OF THE INVENTION:

5 In accordance with one aspect of the present invention, there is provided an electrically conductive shaped article comprising a liquid crystal polymer, poly(styrene-co-maleic anhydride) and conductive filler.

Preferably, the shaped article comprises:

- 10 (a) from about 0.5 wt% to about 40 wt%, preferably from about 1 wt% to about 30 wt%, most preferably from about 5 wt% to about 20 wt%, of the liquid crystal polymer;
- (b) from about 0.5 wt% to about 40 wt%, preferably from about 1 wt% to about 30 wt%, most preferably from about 5 wt% to about 20 wt% of the poly(styrene-co-maleic anhydride); and
- 15 (c) from about 20 wt% to about 99 wt%, preferably from about 60 wt% to about 98 wt%, most preferably from about 70 wt% to about 90 wt% of the conductive filler.

Preferably, the electrically conductive shaped article is a conductive flow field separator plate for use in fuel cells such as direct methanol fuel cell, hydrogen fuel cell and any other known to those skilled in the art.

20 Other applications include electrosynthesis.

In accordance with a second aspect of the present invention, there is provided a method of making a conductive flow field separator plate having reduced resistivity, and lower cost comprising the steps of:

- 25 (a) blending a liquid crystal polymer, poly(styrene-co-maleic anhydride) and conductive filler together to form a blend; and
- (b) compression moulding the blend to form the conductive flow field separator plate.

30 Preferably, step (a) of the method comprises blending the following components:

- (a) from about 0.5 wt% to about 40 wt%, preferably from about 1 wt% to about 30 wt%, most preferably from about 5 wt% to about 20 wt%, of the liquid crystal polymer;
- (b) from about 0.5 wt% to about 40 wt%, preferably from about 1 wt% to about 30 wt%, most preferably from about 5 wt% to about 20 wt% of the poly(styrene-co-maleic anhydride); and

- (c) from about 20 wt% to about 99 wt%, preferably from about 60 wt% to about 98 wt%, most preferably from about 70 wt% to about 90 wt% of the conductive filler.

The conductive compositions of the present invention can be
5 molded into conductive plates through a variety of different molding methods including compression molding, injection molding, injection-compression molding, extrusion, calendering, transfer molding or a combination of them. Based on the melting range of the resins, the compositions can be compounded and molded in the temperature range
10 from 150°C to 380°C and preferably from 200°C to 350°C.

BRIEF DESCRIPTION OF THE DRAWINGS:

The preferred embodiments of the present invention will be described with reference to the accompanying drawings:

Figure 1(a)-(e) illustrate the temperature dependence of bipolar
15 plate conductivity measured at various pressures;

Figure 1(f) illustrates the drop in resistivity of LCP containing plates in comparison to SMA containing plates measured at 500 psi and various temperatures.

Figure 2 illustrates the decrease in plate density as a function of
20 SMA content in the plates.

Figure 3(a) and (b) illustrate the dependence of viscosity on temperature for various blends of SMA and LCP at a shear rate of 1000 s⁻¹ and 10000 s⁻¹, respectively.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS:

25 The preferred embodiments of the present invention will now be described with reference to the accompanying figures.

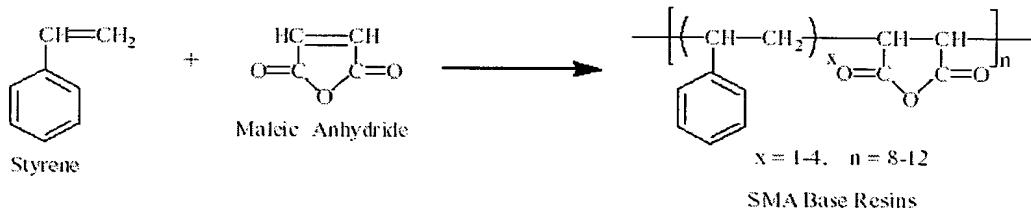
It has been found that conductive flow field separator plates made of a blend of liquid crystal polymer (LCP), poly(styrene-co-maleic anhydride) (SMA) and graphite fillers can be at least as conductive as
30 plates made from blends of LCP and graphite filler only. LCP is very expensive relative to the cost of SMA, therefore, reducing the amount of LCP required in the blend to make the plate reduces the overall raw material cost of the plate. Also, the incorporation of SMA to LCP helps to make the plates lighter.

35 Preferably, the blend used to make the conductive plates comprises:

- (a) from about 0.5 wt% to about 40 wt%, preferably from about 1 wt% to about 30 wt%, most preferably from about 5 wt% to about 20 wt%, of the liquid crystal polymer;
- (b) from about 0.5 wt% to about 40 wt%, preferably from about 1 wt% to about 30 wt%, most preferably from about 5 wt% to about 20 wt% of the poly(styrene-co-maleic anhydride); and
- (c) from about 20 wt% to about 99 wt%, preferably from about 60 wt% to about 98 wt%, most preferably from about 70 wt% to about 90 wt% of the conductive filler, preferably graphite filler.

Further, depending on the amount of SMA incorporated into the LCP, the raw material price for making the conductive plates is reduced by 20-50% due to the decrease in the amount of LCP needed. The cost of SMA is approximately 10% that of LCP.

Poly(styrene-co-maleic anhydride) is formed from the copolymerization of styrene with maleic anhydride. The reaction is as follows:



SMA, also known as poly(styrene-co-maleic anhydride), has high functionality, high thermal properties and good resistance to acidic environments. Generally, the SMA has from about 1% to about 75%, preferably from about 1% to 50%, most preferably from about 1% to about 32%, maleic anhydride moieties. The preferred grades of SMA are supplied by Nova Chemicals, Beaver Valley, PA under the trade name of DYFLARK®332 and Dylark®232. Rubber filled SMA grades are also available from Nova Chemicals, if high impact strength is required. DYFLARK®332 is a clear grade of SMA containing about 14% maleic anhydride moieties and DYFLARK®232 only 8%. Another source of preferred SMA is Chemcor Inc., NY, which supplies SMA in an emulsion form under the trade name of SMA1000®. The properties of SMA1000® emulsion include: 1:1 ratio of styrene : maleic anhydride, 25% solids, and the melting point of the dried emulsion is in the range of 150°C to 170°C.

A preferred form of LCP for use in the present invention is liquid crystalline polyester, which exhibits excellent chemical resistance, thermal stability and gas barrier properties. Preferred LCPs are Liquid Crystalline Polyesters sold by E.I. DuPont de Nemours under the trade names
5 ZENITE®2000, ZENITE®400, ZENITE®6000, ZENITE®800.

In order for the plates to have the desired electrical conductivity, the plates should be made of a blend containing conductive filler. Preferred conductive fillers are graphite fillers such as graphite fibres and graphite powders. Conoco supplies graphite powder under the trademark
10 THERMOCARB®. Also preferred as the conductive fillers are carbon nanotubes.

The method of making the conductive fuel cell collector plates includes the steps of:

- 15 (a) blending a liquid crystal polymer, poly(styrene-co-maleic anhydride) and conductive filler together to form a blend; and
- (b) moulding the blend to form the conductive flow field separator plate.

Preferably, the separator plate may be molded using a molding process such as compression, injection, extrusion, including molding the
20 flow field pattern onto a surface or both surfaces of the plate.

Alternatively, the flow field pattern may be machined onto the surfaces after the plate has been molded. The plates generally have a total cross sectional thickness of from about 0.5 mm to about 5 mm.

The following examples illustrate the various advantages of the
25 preferred composition and method of the present invention.

EXAMPLES:

In these examples, plates were made from one or more polymers (non-conductive portion) and graphite powder and filler (conductive portion). The two polymers used were SMA and LCP. Two types of
30 conductive fillers were used: graphite powder and graphite fiber. Conoco supplied both types of conductive fillers. The conductive fillers used had the following properties:

Synthetic graphite powder:

- a. Particle size distribution range: from 20 μm to 1500 μm ;
35 Average size: 240 μm BET (Multi-point or Single-point, Brunauer, Emmett and Teller method)
- b. Surface Area: 2-3 m^2/g
- c. Bulk density: 0.5-0.7 g/cm^3

d. Real density: 2-2.21 g/cm³

Pitch-based graphite fiber with no surface sizing or treatment

e. Fiber length distribution range: from 15 to 500 µm; Average size =106 µm

5 f. Fiber diameter 8-10 µm

g. Bulk density 0.3-0.5 g/cm³

h. Real density 2-2.21 g/cm³

Through plane resistivity was measured using the contact resistance method in which the conductive flow field plate was placed between two gold plates at 314 psi. A power supply was used to send a known current through the gold plates and resistance (R) is calculated using Ohm's Law, i.e., the formula $I = V/R$, where I is the current in amps and V is the potential drop in mV as read from the multimeter. Through plane resistivity can be calculated using the equation: $\rho = R \times A/T$, where A is the area of the plate and T is the thickness of the plate.

10 15 EXAMPLE 1.
This example compares the through plane resistivity of plates made with SMA as binder to that of LCP. Nova Chemicals, Beaver Valley, PA supplied SMA under the trade name of DYFLARK®232, and E.I. DuPont de Nemours supplied LCP under the trade name of ZENITE®800. The formulations are set out in Table 1.

Table 1:

Ingredients (by weight %)	Formulation#	
	1	2
Graphite fiber, %	20	20
Thermocarb™ (graphite powder), %	57	55
Dylark™232 (powder), %	0	25
Zenite™ 800, %	23	0

25 Both formulations were melt blended. Formulation (1) was compounded using a Coperion Buss® kneader at 310°C-320°C. Formulation (2) was melt blended in a Brabender™ lab mixer at 230C and 40 rpm. The compounded material was cooled to room temperature and then molded into a 4"x4" plate. The molding procedure comprised 30 preheating the mold to 235°C with 50 g of the weighed materials for 10 min under a pre-clamp force of 2000 lbs; increasing the clamp force to

8000 lbs and holding for 10 min; increasing the clamp force to 10000 lbs for 2 min and then cooling down the mold to 90°C before ejecting the plate. Both plates were scrubbed on both surfaces with a Scotch-Brite™ pad and subsequently subjected to through plane resistivity

5 measurements at various temperatures and pressure. The results are shown in Figures 1 (a) to (e).

The results illustrate a higher reduction in resistivity of the SMA containing plate (Formulation 2) at various temperatures and at a 500 psi sample pressure in comparison to the LCP plate (Formulation 1). This
10 difference becomes more significant at the typical PEM fuel cell operation temperature range from 80-100°C.

Example 2.

This example compares the conductivity property of bipolar plates, which use LCP only as a binder, to those that use blends of LCP and
15 SMA. Approximately 250g of Formulations 3-7 (see Table 2) were melt-blended using a Brabender® melt mixer. The bowl temperature was set at 260°C and the mixer speed was kept constant at 40 rpm. All samples were mixed at these conditions for a maximum of 2 minutes.

20 **Table 2:**

Ingredients (wt %)	Formulation#				
	3	4	5	6	7
Graphite fiber	20.00	20.00	20.00	20.00	20.00
Thermocarb™ (graphite powder)	57.00	57.00	57.00	57.00	57.00
Zenite®800	23.00	21.00	18.00	13.00	3.00
Dylark®232	0.00	2.00	5.00	10.00	20.00

The melt mixed material was used to mold flat 4"x4" plates on a 50 ton Wabash® compression press. The platen temperature was set at 280°C and 50g of material was fed into the mold cavity. This material was
25 preheated for 10 minutes under a pre-clamp force of 2000 lbs. The clamp force was then increased to 8000 lbs and held there for 10 minutes. Subsequently, the clamp force was increased to 10000 lbs and kept there for 2 minutes. The plates were cooled to 90°C under this pressure and finally the mold was opened to eject the molded plate. At least 4 plates
30 were made with each formulation. These plates were subject to through

plane resistivity testing as described above. The results are listed in Table 3.

It can be seen that the replacement of Zenite® 800 with a blend of Zenite® 800/Dylark® 232 results in lower through plane resistivity.

5

Table 3:

Formulation	Through plane Resistivity, Ω.cm	Standard deviation
3	0.050	0.004
4	0.032	0.004
5	0.035	0.005
6	0.035	0.002
7	0.038	0.001

Example 3:

The following example investigates the effect of incorporating SMA 10 into bipolar plates made of LCP and graphite powder. Before use, both ZENITE®800 and DYLARK®332 were cryogenically ground to less than 1000 microns particle size in a BRINKMAN® lab scale cryogenic grinder. Table 4 below sets out the formulations used in this example.

15 Table 4: Formulations used in Example 3, by weight percent:

Ingredients:	Formulation, by weight %				
	8	9	10	11	12
LCP (ZENITE®800)	30.00	27.00	22.50	15.00	0.00
THERMOCARB® (graphite powder)	70.00	70.00	70.00	70.00	70.00
DYLARK® 332 (powder)	0.00	3.00	7.50	15.00	30.00

The procedure used to make plates from formulations 8 to 12 was as follows:

Step 1: Preparation of formulation:

- 20 a. About 200g of each formulation was dry mixed by weighing the ingredients of each formulation in a polyethylene bag.
- b. The bag containing the pre-weighed ingredients was inflated and the opening was tied.
- c. The bag was shaken rigorously for 5-10 minutes by hand.

25 Step 2: Viscosity measurements:

Before compounding the formulations, the dependence of viscosity on temperature for each formulation was determined using steady shear temperature sweep in a parallel plate rheometer. All formulations have a viscosity of 10^6 Pa*s at the temperatures mentioned in Table 5 below.

5

Table 5: Temperatures at which the viscosity is 10^6 Pa*s:

	Formulation				
	8	9	10	11	12
Temperature (°C)	290	265	255	245	235

For this example, therefore, the melt mixing and compression molding of the plates was done at these temperatures for each of the
10 respective formulations.

Step 3: Compounding:

Compounding was done in a BRABENDER® compounder. The mixer speed was kept constant at 40 rpm for all the formulations. 200 grams of each formulation was fed slowly into the hot bowl while the mixer
15 was rotating. The compound was mixed for 2 min after the 200 g of mixture was completely fed into the bowl. The bowl was then opened and the material removed. The material was separated into smaller portions before cooling. The bowl temperature used for each formulation was the same as set out in Table 5 above, such that the resulting viscosity of all
20 the formulations was kept constant at 10^6 Pa*s.

Step 4: Compression molding:

A 4"x4" blank plate mold was preheated to the temperatures mentioned in Table 5 above depending on the formulation used. 50 g of the compounded formulation was placed in the mold for 10 min under a clamp force of 2000 lbs. The clamp force was then increased to 8000 lbs and maintained 10 min. Thereafter, the clamp force was increased to 10000 lbs and maintained for 2 min. At this point, the mold was cooled to a temperature of 90°C while maintaining the same clamp pressure using water-cooling. Once the mold and plate were cooled to 90°C, the clamp
25 was opened thereby releasing the pressure. The mold was then allowed to cool to room temperature prior to removing the formed plate.
30

Two plates were compression molded using this procedure for each of formulations 8 to 12. These plates were then analyzed for through

plane resistivity using through plane resistance press, flex properties and density.

- The results of the through plane resistivity analysis are set out in Table 6. It can be seen that the through plane resistivity of the plates made with formulation 8-12 are very close to each other and lie well within the acceptable values for fuel cell application.

Table 6: Through plane resistivity results:

Plate Made From Formulation:	Wt% SMA	Through Plane Resistivity, (mΩ.cm)	Standard deviation
8	0	47.50	2.77
9	3	52.00	2.95
10	7.5	47.70	2.26
11	15	62.70	1.25
12	30	58.93	6.51

- The flex properties of the plates molded from each of the formulations 8 to 12 were tested using method ASTM D-790. The span was 2.5 inches and a crosshead speed of 0.08 in/min was employed. The results are set out in Table 7. The flex stress and strain results lie very close to each other considering 10% experimental error. Both through plane resistivity and flex properties of plates made with formulations 8 to 12 show that there is insignificant effect of addition of SMA to a blend of LCP and graphite powder.

Table 7: Flex properties of molded plates:

Plate Made From Formulation:	Wt% SMA	Strain (in/in)	Standard deviation	Yield Stress (psi)	Stanadard deviation
5	0	0.004	0.001	4772.13	506.2
6	3	0.005	0.001	4403.918	692.6
7	7.5	0.004	0.001	4687.72	356.4
8	15	0.003	0.001	3988.2	433.8
9	30	0.003	0.001	4562.34	955.1

- The density of the plates made from each of the formulations was determined by cutting a small piece out of the molded plate and then measuring its density using the density determination kit supplied by OHAUS® model AP210S. The water temperature was 23°C, and its corresponding density is 0.998 g/ml. The density results are set out in

Table 8 and plotted in Figure 2, which shows the density of the molded plate as a function of the % weight of SMA in a LCP, SMA, 70% graphite powder tri-blend.

5 Table 8. Density of plates molded using formulations 8 to 12:

Plate made from formulation	Run #	Density (g/ml)	Avg. Density (g/ml)	Std. Deviation
8	1	1.8195		
	2	1.8162	1.8182	0.0018
	3	1.8189		
9	1	1.7852		
	2	1.7790	1.7829	0.0034
	3	1.7844		
10	1	1.7675		
	2	1.7661	1.7685	0.0031
	3	1.7720		
11	1	1.7321		
	2	1.7353	1.7323	0.0029
	3	1.7294		
12	1	1.6191		
	2	1.6220	1.6244	0.0068
	3	1.6320		

The following conclusions can be reached from Example 3:

a. The weight of plates made with a SMA, LCP and graphite powder tri-blend decreases as the amount of SMA in the blend is increased. This plate weight reduction is accompanied with no significant effect to plate through plane resistivity and flex properties.

b. The price of plates incorporating SMA is much less than that of plates made with LCP only because of the significantly lower cost of SMA. Therefore, the cost of making conductive plates is reduced without significantly affecting the plates' through plane resistivity and flex properties.

Example 4:

Nova Chemicals, Beaver Valley, PA supplied SMA under the trade name of DYLARK®332. This is a clear grade containing about 14% maleic anhydride. E.I. DuPont de Nemours supplied LCP under the trade name of ZENITE®2000. This is a lower melt temperature grade of LCP (melting point: 230°C). Both these polymers were cryogenically ground to less than 1000 microns using a BRINKMAN® lab scale cryogenic grinder.

About 50 grams of each of the formulations mentioned in Table 9 below were made:

5 Table 9. Formulations for Example 4. All compositions are by weight percent.

Ingredients	Formulation#, by weight %		
	13	14	15
LCP (ZENITE®2000)	30	20	10
Graphite powder	40	60	80
SMA(DYLARK®332 powder)	30	20	10

The dry mixing of each of these blends was done in the following way:

- a. The ingredients of the blends were weighed in a polyethylene bag.
 - 10 b. The bag containing the pre-weighed ingredients was inflated and the opening was tied.
 - c. The bag was shaken rigorously for 5-10 minutes by hand.
- The blended powder was then emptied directly into the mold. This mold was used to compression mold 4" x 4" x 1/8" plates.
- 15 Compression molding procedure involved pressing the mold at 260°C at a pressure of 2 tons for 10 minutes. Thereafter the pressure was increased to 7.5 tons for 10 minutes, followed by 10 tons for 2 minutes. After this, the mold was cooled from 260°C to 90°C while maintaining the pressure at 10 tons. The conductivity properties of the plate were measured and reported in Table 10 below:

Table 10. Resistivity of Plates Made From Formulations 13, 14 and 15:

Plate made from formulation	Plate thickness (mm)	Through plane resistivity (mΩ.cm)
13	2.91	9881
14	2.67	215
15	2.53	62

25 Example 5.

This example compares the rheological properties of pure SMA and LCP with that of LCP/SMA blends. Nova Chemicals, Beaver Valley, PA supplied SMA under the trade name of DYLAIRK®332. E.I. DuPont de

Nemours supplied LCP under the trade name of ZENITE®800, which melts at above 260°C. Formulations 16-21 listed in Table 11 were first mixed together in an inflated bag and then melt blended using a 25mm W&P extruder. The extrusion conditions are listed in Table 12.

5

Table 11: Formulations for Example 5.

Ingredients (wt %)	Blend Compositions					
	16	17	18	19	20	21
LCP (ZENITE®800)	0	20	40	60	80	100
SMA(DYLARK®332)	100	80	60	40	20	0

Table 12:

	17	18	19	20
Zone 1 (°C)	250	250	250	250
Zone 2 (°C)	255	255	255	255
Zone 3 (°C)	253	258	254	258
Zone 4 (°C)	261	260	260	260
Die (°C)	265	265	265	265
Screw RPM	275	270	250	250
Torque, %	40	40	44	46
Die pressure, psi	108	107	89	81
Melt temperature, °C	268	265	265	265
Approximate throughput, kg/hr	6	6	6	6

10 The extruded strands were cooled in a water bath and fed into a Scheer® strand cutter Model SGS. The resulting pellets were subjected to capillary rheometry. A capillary rheometer from Kayeness Inc. a Dynisco Company model LCR5000 or Galaxy V model #8052 with 4.5kN load cell was used for obtaining the apparent viscosities at temperatures in
15 between 240°C and 320°C.

14 The apparent viscosity obtained at a shear rate of 1000s⁻¹ is shown in Figure 3a. It can be noted that at temperatures above 260°C the addition of more than 60% SMA to LCP increases its viscosity. This temperature also happens to be the melt temperature of LCP. Therefore
20 use of more than approximately 50% (interpolated value) by weight SMA increases the viscosity of the LCP/SMA blend to higher values than the viscosity of pure LCP. At a shear rate of 10000s⁻¹ (Figure 3b), blends with SMA content above 40% have a viscosity higher than pure LCP at temperatures below 280°C. Therefore adding more than 40% by weight

SMA to LCP increases the blend's viscosity to levels higher than pure LCP for shear rates in between 1000-10000s⁻¹.

Example 6:

In this example, plates were made from a mixture of LCP, SMA and graphite powder using a wet blending technique. ZENITE®800 was cryogenically ground to about 500 micron average size. SMA was obtained in an emulsion form from Chemcor Inc., NY under the trade name of SMA1000®. The properties of SMA1000® emulsion include: 1:1 ratio of styrene : maleic anhydride, 25% solids, melting point of dried emulsion is in-between 150-170°C.

Table 13. Formulation 22 for Example 6:

Ingredients	Formulation 22 (wt. %)
LCP (ZENITE®800)	16.7
Graphite powder	66.7
SMA1000® (dried content)	16.7

The liquid blending procedure used was as follows:

- 15 a. The ingredients of the formulation were weighed separately.
- b. 40g of graphite powder were added slowly to a beaker containing 600 ml of tap water, while stirring.
- c. 10g of ZENITE®800 powder was then added slowly.
- d. Stirring continued until a slurry was formed and then 40g of SMA1000® emulsion was added.
- e. The slurry was heated while continuously stirring with a magnet until the water evaporated and a paste was obtained.
- f. The paste was placed in a vacuum oven at about 170°C for 6 hours until all moisture was removed.
- 20 25 This dried blend was then compression molded at 320°C using the same pressure cycle as in Example 1 in order to make a 4"x4"x1/8" plate. The conductive properties of this plate were measured as follows:

Table 14. Resistivity of Plates Made From Formulation 22:

Plate made from formulation	Sample thickness (mm)	Average resistivity from 4 point probe (mΩ.cm)	Through plane resistivity (mΩ.cm)

4	3.24	7.2	55.8
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Although the present invention has been shown and described with respect to its preferred embodiments and in the examples, it will be understood by those skilled in the art that other changes, modifications,
5 additions and omissions may be made without departing from the substance and the scope of the present invention as defined by the attached claims